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Biofuel economics in a setting of multiple objectives and unintended consequences

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A R T I C L E I N F O

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This paper examines biofuels from an economic perspective and evaluates the merits of promoting biofuel production in the context of the policies' multiple objectives, life-cycle implications, pecuniary externalities, and other unintended consequences. The policy goals most often cited are to reduce fossil fuel use and to lower greenhouse gas emissions. But the presence of multiple objectives and various indirect effects complicates normative evaluation. To address some of these complicating factors, we look at a several combinations of policy alternatives that achieve the same set of incremental gains along the two primary targeted policy dimensions, making it possible to compare the costs and cost-effectiveness of each combination of policies. For example, when this approach is applied to U.S.-produced biofuels, they are found to be 14–31 times as costly as alternatives like raising the gas tax or promoting energy efficiency improvements. The analysis also finds the scale of the potential contributions of biofuels to be extremely small in both the U.S. and EU. Mandated U.S. corn ethanol production for 2025 reduces U.S. petroleum input use by 1.75% and would have negligible net effects on CO_2 emissions; and although EU imports of Brazilian ethanol may look better given the high costs of other alternatives, this option is equivalent, at most, to a 1.20% reduction in EU, gasoline consumption.

Contents

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1. Introduction

The belief that biofuels can reduce dependency on fossil fuels and mitigate climate change has led many governments to promote their production and use as substitutes for gasoline and petroleum-based diesel, using mandates and subsidies. With the added suggestion that biofuel production could encourage rural economic development and poverty alleviation, biofuel subsidies in 2006 amounted to $11 billion ($\$11 \times 10^9$) in the leading OECD producing countries [1]. The largest biofuel programs are in the U.S., the EU, and Brazil, but many developing countries are also implementing or considering similar policies to encourage domestic biofuel production.

Renewable energy promotion has become a policy priority in many countries, and biofuels are one type of renewable energy. However, as with other renewable energy options, the emergence of biofuel promotion has not been based on, or preceded by, a detailed analysis of its prospects, implications, and the potential for achieving their intended objectives [2] and hence may allocate billions of tax-payers dollars inefficiently. The picture is further clouded by the fact that biofuels constitute an indirect means to achieve their central goals, so that the connections between increased biofuel production and the resultant reductions in both fossil fuel use and greenhouse gas (GHG) emissions are far from obvious. Moreover, these efforts may cause externalities in the form of feedback effects and other unintended consequences, both pecuniary and non-pecuniary that impose additional costs on society. The general theory of second-best [3] warns us that government interventions to correct market failure may actually reduce welfare because other optimality conditions do not hold. This possibility becomes particularly important when considering (a) the direct and indirect ways in which large-scale biofuel production alters existing uses of energy and land and (b) other impacts via pecuniary and non-pecuniary externalities.

Indeed, only recently has attention been drawn to some of the effects of biofuels on food prices, energy use, land-use change and carbon emissions. Given both the lacking transparency and emerging evidence of these effects, it is important to examine what we now know and to illuminate this information in ways that will inform good policy decisions. The two main questions policy makers need to have answered in relation to the central policy goals are: (a) How do the costs of biofuels compare to other options? and (b) Can biofuels be made available on a large enough scale to make significant progress toward those goals?

This paper's aim is to investigate these two critical questions. Since biofuels and alternative interventions affect both the use of fossil fuels and GHG emissions to different extents, we first develop an explicit cost-effectiveness measure to compare options in equivalent terms, i.e., for the same set of primary outcomes. With this measure the relative costs of various policy alternatives can then be directly assessed in relation to the policies' multiple ends or goals. This is an important distinction from prior research that commonly ignores biofuel policies' complexity by focusing on only a single policy dimension or that assumes simple gallon for gallon fuel substitution without considering the multitude of associate effects. Finally, we examine the potential scope of biofuels' contribution toward their stated policy objectives.

There are some important technical and engineering aspects of biofuels that, because of their complexity, warrant some attention before developing our framework for evaluating the two questions posed. In Sections 2 and 3, summaries of background information and key issues are presented to provide important context (although less technical inclined readers may skip Sections 2 and 3). Section 4 develops a framework for estimating the cost-effectiveness of biofuels in comparison to other policy options and is followed in Section 5 by a presentation of the data and estimations undertaken for each option. The results are described in Section 6, and Section 7 offers some concluding thoughts.

2. Background

Although biofuel promotion has accelerated over the past decade, production and use of ethanol as a transportation fuel has been supported in the U.S. since 1978 and in Brazil since the 1930s. Europe's experience with biofuels is more recent. Among renewable energy options, biofuels have attracted attention in part because they are liquid fuels that can be easily used in motor vehicles, and in some cases with little or no modification of existing gasoline or diesel fuel engines.

In the U.S., federal and state ethanol programs were initially aimed at supporting farm prices and farm incomes. Later the rationale for these programs shifted to environmental quality, and more recently to energy security/independence and reduced GHG emissions [4]. Federal subsidies have ranged from $0.40 to $0.60/gallon and are currently at $0.45. When state programs and subsidies for start-up and investments are included, the total subsidy in 2006 is estimated to range from $1.05 to $1.38/gallon [1]. Federal legislation has, in the past decade, established a schedule of renewable fuel production targets, the most recent being the Energy Independence and Security Act of 2007 which sets targets for renewable fuels consumption (rising from 9 billion gallons in 2008 to 36 billion gallons in 2022). The volumetric requirements by renewable fuel type were adjusted in 2010 under the revised Renewable Fuels Standard (RFS2). The total mandate of 36 billion gallons by 2022 requires cellulosic ethanol production to rise from 0.1 billion gallons in 2010 to 16 billion gallons, corn ethanol production to rise to 15 billion gallons, and an additional 5 billion gallons of non-cellulosic "advanced" biofuels including a minimum of 1 billion gallons of biodiesel (primarily soybean-based).[1] U.S. current corn ethanol capacity is approximately 13 billion gallons including idled capacity.

Ethanol production for sugarcane in Brazil dates back to the 1930s. The Brazilian government began in 1975 a "pro-alcohol" program to produce ethanol from cane biomass using quotas, fixed prices, and subsidized loans [5]. Between 1997 and 1999, sugar and ethanol prices were deregulated and flex-fuel vehicles introduced so that consumers could choose their desired fuel mix (all gasoline in Brazil is blended with 20–25% ethanol). National production in 2008 was 6.5 billion gallons, exceeded only since 2006 by the U.S.

Europe's experience with biofuels started in the 1990s when several countries started producing biofuels in response to concerns about energy security. Beginning in 2000, the EU saw a number of renewable energy proposals put forward. A biofuel target for 2% of transportation fuel by 2005 and 5.75% by 2010 was established in 2003, only to be abandoned in 2005 when it became clear that production would fall 1.4% short of the 2% target. In 2006, the EU replaced quantitative targets with a strategy aimed at continued promotion of biofuels in the EU and developing countries, support for research into second-generation biofuels such as cellulosic ethanol, and exploration of opportunities for developing countries to produce biofuel feedstocks and biofuels [6]. In 2009, a new EU mandate was established that calls for 10% biofuel content in transportation fuels by 2020.

[1] Cellulosic ethanol is derived from lignocelluloses materials in wood, grass, corn stover, or other non-edible parts of plants. Non-cellulosic advanced biofuels include biodiesel derived from algae.

3. Issues affecting biofuels' potential

Biofuels were initially seen as an easy solution to energy and environmental problems because they represented energy grown by farmers and captured from the sun that would be carbon neutral because the CO_2 emitted when burning the biofuel was simply the release of CO_2 previously absorbed from the atmosphere by the plants grown as feedstock. In this "win–win" view, a clean, renewable energy in liquid form (so it could be used as a transportation fuel) could be grown domestically to reduce dependency on fossil fuels, save foreign exchange, create jobs, and protect the environment. By now we understand, however, that the biofuel picture is more complex given the resources required to produce feedstocks in large quantities, as well as the externalities and indirect market effects (pecuniary externalities) caused by large-scale production of biofuels.

These considerations can be organized under three topics: life-cycle analysis, pecuniary externalities, and non-pecuniary externalities. First, life-cycle analysis for biofuel production reveals that both energy and GHG accounting involve the use of fossil fuels, which in turn imply GHG emissions unrelated and in addition to the CO_2 absorbed by immediate plant growth. Second, large scale biofuel production generates pecuniary externalities that raise concerns about food prices and cause changes in land use. While these market effects may represent negative externalities narrowly defined, to the extent that food security and distributional effects are part of concern, these pecuniary effects deserve attention. Third, direct and indirect externalities raise additional issues related to land use, carbon emissions, water scarcity, and air pollution. These aspects of biofuel policies potentially lead to revisions in their expected energy and climate change gains, and in doing so alter significantly our understanding of biofuels' costs as well as the scale of biofuels' possible contribution toward the stated program goals.

3.1. Life cycle analysis of biofuels

The perception that consuming a gallon of ethanol eliminates the use of a gallon of gasoline is misleading for at least two reasons. First, ethanol contains less energy per gallon than gasoline. And second, because fossil fuels are used in the production of biofuels and their feedstocks, the overall net contribution of biofuels to energy availability requires deducting the input energy used in the production process from the gross energy content of the biofuel. Life cycle analysis (LCA) looks at the entire process of producing and combining inputs including transportation to the final place of consumption. LCA is often used for energy accounting, but it can also be applied to fully account for carbon emissions, water use, or other materials, yielding a measure of the net energy or net materials use. In the case of biofuels, the solar energy contained in the feedstock is considered "free", and is therefore ignored. As a result, biofuel production creates an energy gain rather than an energy loss – but the gain will be less than the amount of energy in the fuel.

Given the objectives of reducing fossil fuel use and GHG emissions, LCA permits evaluation of the net contribution of biofuels. There are several ways to express the relationship between fossil fuel energy inputs used to produce biofuels and the energy contained in the fuel itself. The ratio of fossil fuel inputs to energy in fuel provides a succinct indicator. For fossil fuels themselves, of course, this ratio will be greater than one since some fossil fuel is needed to extract, transport and refine gasoline from crude oil. Central estimates of those ratios are 1.23 for gasoline and 1.15 for petroleum diesel. For biofuels, these ratios vary considerably across fuels, reflecting a wide range in net energy contributions, the most cited values being 0.66 for corn ethanol, 0.38 for soy biodiesel, and 0.08 for cellulosic ethanol.

Because biofuels are produced using fossil fuel inputs (including nitrogen fertilizer for corn production), they are not carbon neutral. Similar to the LCA energy accounting life-cycle carbon emissions can also be evaluated for biofuels. Carbon LCA depends greatly on technology and types of fossil fuel used. Central estimates for corn ethanol suggest a 20% reduction in CO_2 emissions per MBTU (million British Thermal Units) when substituting for gasoline. The reduction is 40% for biodiesel in the U.S. and Europe, and 78% for Brazilian sugarcane ethanol [7].

LCA provides a useful first indication of the energy or GHG consequences of using biofuels. But because it does not account for behavioral responses or market effects, LCA can be a poor indicator of the general equilibrium effects of introducing biofuels and overstate their benefits. Discussed below are the potential pecuniary externalities occurring in product and input markets due to biofuel production, as well as the consequent externalities, which occur through these indirect changes and affect both energy and GHGs.

3.2. Pecuniary externalities and food prices

Biofuel production and consumption create pecuniary externalities by shifting supply and demand in input and output markets. How these effects play out, however, will depend on the kind of policy used to promote biofuel consumption, and to what extent the costs of biofuels are born by consumers. Biofuel production and consumption can be promoted with subsidies, regulatory requirements, or other instruments. Except where noted, the analysis below assumes that biofuels are subsidized at a rate that matches the cost per BTU for gasoline (or petroleum diesel in the case of biodiesel).

When consumers switch to biofuels the demand for gasoline will decrease leading to a decline in gasoline prices. Lower gasoline prices, however, will increase the quantity of gasoline demanded so that the net decrease in gasoline consumption (and associated fossil fuel inputs and CO_2 emissions) can be expected to be less than the increase in biofuel consumption. This second-order effect may be offset to the extent that biofuel mandates (like the 10% requirement for gasoline in the U.S.) raise gasoline costs when the more costly biofuels are blended with gasoline. It is difficult to estimate which effect dominates at any given point in time, but the net result will be marginal at best and can therefore be quantitatively ignored. The subsequent analysis, thus assumes a BTU-for-BTU substitution from petroleum fuel to biofuel.

Co-products in biofuel production including distiller dry grains (corn ethanol) and soybean meal are marketable as a component in livestock feed, and so these products are likely to displace existing animal feed production. Because the displaced animal feed production would have required energy to produce comparable energy-laden feed rations, an energy "credit" is generally assigned in the biofuel energy accounting (outside of LCA). This "credit" recognizes this substitution effect that "saves" energy at the level of the economy even though it does not occur within the standard LCA boundaries. In the analysis below co-product energy credits are included.

Biofuel feedstock production requires large areas of agricultural land. Drawing land into the biofuels market, therefore reduces the supply of land for food, feed and other agricultural production. This shift puts upward pressure on land prices but, more importantly, reduces the supply of food and feed. This leftward shift in the food supply schedule leads to two very important effects: (a) an increase in food prices, and (b) an expansion of agricultural production in other areas not previously under cultivation.

Beginning in 2006, world food prices rose dramatically into 2008, with prices for corn and other staple foods such as rice,

soybeans and wheat doubling. The increases caused protests and political unrest in many parts of the world, with biofuels taking much of the blame. Numerous studies have since attempted to assess the causal factors leading to these sharp increases in worldwide food prices. In general they agree that multiple factors contributed: rapid economic growth in some developing countries leading to increased demand; weather and crop disease shocks in 2006–2007, devaluation of the U.S. dollar, and growth in the production of biofuels [8]. Most studies also concluded that biofuel policies were a significant factor, with estimates of the share of food price increases attributable to biofuel policies ranging from 10% [9] to 75% [10]. Using a multi-market analysis, Rajagopal et al. [11], for example, conclude that about one-quarter of food price inflation in 2007–2008 was due to biofuels. The connection between biofuels and increasing food prices drew worldwide attention to the potential adverse pecuniary effect of biofuel promotion and has been a significant factor in the decline in public support for biofuel policies in many countries.

3.3. Externalities, indirect land use change

The effects of supply or demand shifts tend to be viewed neutrally in economics as pecuniary externalities, but not as inefficient. Indeed, such pecuniary externalities may represent welfare improvements if they arise as a result of interventions to correct market failures. In the presence of other market failures, however, the Theory of Second Best implies that such market adjustments can be welfare reducing. Food price increases caused by biofuel production are one example of a pecuniary externality that causes food insecurity among the poor and potentially leads to significant human suffering.

Land markets are also affected. Most biofuels require land-intensive feedstock production, which increases the demand for (cultivable) land. The resulting incremental increase in the equilibrium quantity of land under cultivation may occur in a different location than where the biofuel feedstock is grown. Indeed, if feedstock production displaces food production in one area, food price adjustments are likely to bring additional land into cultivation elsewhere. Although this is a standard market adjustment phenomenon, it has become a pivotal and controversial issue for biofuels because expanding production onto previously uncultivated land releases significant quantities of carbon that have accumulated over long periods in soil and vegetation. These indirect external effects from biofuel production can generate carbon emissions in excess of the emissions reductions promised by substituting biofuels for gasoline (even when averaged over a 30-year period). Therefore, the magnitude and consequences of indirect land use change effects (ILUCs) need to be considered when evaluating biofuels.

Estimates of the magnitude of ILUCs were first presented by Searchinger et al. [44], who included both the reduced emissions from substituting biofuels for gasoline as well as the increased emissions the ILUC effects. Compared to a simple LCA that showed a reduction of 20% in CO_2 emissions for corn ethanol, Searchinger et al.'s inclusion of ILUC effects produced an estimated increase of 93% in emissions. However, more recent estimates based on revised global models forecasted smaller ILUC effects. In the case of corn ethanol, Tyner et al. [12] suggest that the ILUC effects are sufficiently low so that the net effect from corn ethanol production is a small reduction in CO_2 emissions rather than an increase as suggested by Searchinger et al. [44]. In the case of Brazilian sugarcane ethanol, life-cycle analysis suggests a 75% reduction in GHG emissions, whereas the inclusion of land-use changes produces an estimated 125% increase compared to gasoline. This large effect in Brazil occurs as sugarcane displaces rangeland, and rangeland displaces forests and other native habitat [13].[2]

3.4. Jobs and rural development

Job creation and rural development are sometimes mentioned by governments as additional reasons for promoting biofuels. The notion that biofuels could achieve energy security, environmental goals and at the same time create jobs and stimulate rural economies is an appealing prospect. There is little evidence, however, that increased biofuel production will have significant, long-term positive job impacts in rural areas. A typical 100 million gallon ethanol plant provides an estimated 45 jobs. Ethanol subsidies in the U.S. are currently $0.45/gallon, the equivalent of $1 million per job per year. Some proponents estimate substantial indirect job creation, but these projections are based on static, regional input–output models and do not reflect long-term general equilibrium adjustments including shifts in jobs among regions. Indeed, one study modeling the effects of U.S. biofuel mandates on shifts in agricultural production among regions concluded that cellulosic ethanol would expand in the southern states but that it would not provide any additional economic activity because the increase in ethanol output would be offset by a reduction in livestock production [14].

3.5. Policy choice and interactions

The particular policies chosen to promote biofuels will affect its effectiveness, its cost, and also the associated pecuniary externalities and other changes. The net effect of the policies on fuel prices is one important factor. A blend mandate introduced independent of other policies may, to the extent that biofuels are more costly than the fossil fuel with which they are blended, discourage driving and hence lower fossil fuel consumption. The 10% blend requirement for ethanol in gasoline would have such an effect, were it not for the additional policies that subsidize production of ethanol. In the U.S. ethanol costs about 40% more to produce than the cost of gasoline on a BTU basis, and the subsidy per BTU for ethanol is similarly about 40%.

The net effect of combinations of biofuel policies is not always obvious, however. De Gorter and Just [15,16] demonstrate how mandates, taxes and subsidies for biofuels can interact with each other, and with other policies, in ways that significantly alter the social costs and benefits of biofuels. Based on analyses of U.S. corn ethanol production, they find that a biofuel blend mandate can increase or decrease retail fuel prices depending on the relative supply elasticities, but that a biofuel tax credit will always result in lower fuel prices, and hence increased consumption [15]. If tax credits are implemented alongside biofuel blend mandates, the effect of the tax credit will be to subsidize fuel consumption instead of biofuels (relative to a mandate with no subsidy), which will have the effect of increasing oil dependency and CO_2 emissions [15]. Ethanol policies that affect corn prices can exacerbate the inefficiencies of farm subsidies (and vice versa).

[2] An alternative approach taken in a recent National Research Council report involves taking account of the direct land use effects (where the biofuel feedstock is grown) and attributes the ILUC effects to the "second product" that is grown on that land [45]. The ILUC approach, by contrast, involves a "with versus without" analysis to attribute changes associated with a policy promoting biofuels. The latter approach recognizes that the "second product" (i.e., food) has been displaced from one location to another, and any change in its direct land use effects will arise due to that displacement.

4. Analytical framework

While the above discussion underlines the great complexity of assessing biofuels, it also shows that many effects are relatively minor in magnitude. These effects can thus be neglected without changing the general qualitative conclusions. The following analysis therefore takes account of only the main factors impacting the two policy goals (reduced fossil fuel use and reduced GHG emissions), and compares biofuel with other policy options that could also achieve those goals. Sufficient current information is available to permit a reliable estimate of the net gains toward these two goals.

Although a standard approach to evaluating different kinds of policies is benefit–cost analysis, in the context of biofuels, estimating the value of benefits from reduced fossil fuel use and GHG emissions is complex, uncertain and controversial. A benefit–cost analysis would therefore undoubtedly raise questions about the validity of the benefit estimates (see, for example, [17,18]) and distract from questions of cost and cost-effectiveness, which are important by themselves and can be examined independent of the precise benefit measures.

An alternate approach when the main focus of attention is not the benefits of the outcome, but rather the costs of alternative ways to achieve those outcomes, is cost-effectiveness analysis. Cost-effectiveness analysis compares the costs of alternative means for achieving a specific outcome, and thus identifies the least-cost alternative. It has been successfully used in health economics (see, for example, [19]) and has increasingly been employed by economists in addressing environmental policy issues. For example, economists have applied cost-effectiveness to questions of conservation technology adoption [20], selecting biological reserves [21], ecosystem management [22], and pollution control policies [23].

Evaluating biofuels in terms of cost-effectiveness for achieving two central goals – reducing fossil fuel use (both to decrease dependency on petroleum imports and to shift generally toward renewable energy) and reducing carbon emissions – and also examining their scope for furthering those objectives complicates the application of cost-effectiveness analysis since alternative interventions may result in changes that are not directly comparable (e.g., when the relative gains among the multiple goals occur differently). In the current context, certain interventions affect both the use of fossil fuels and GHG emissions (e.g., a gas tax or carbon tax), whereas others address only one objective (e.g., carbon sequestration), and still other interventions may promote one goal but may adversely affect the other (e.g., biofuels that substitute for fossil fuels but increase carbon emissions as a result of land use changes). To evaluate the costs of alternative policies for achieving a common outcome or common combination of outcomes, an explicit cost-effectiveness measure is developed to compare options in equivalent terms, i.e., for the same set of primary outcomes.

Thus our analysis evaluates the direct and quantitative relationship between the ends and means: between the ends of reduced fossil fuel use and reduced GHG emissions, and the means of biofuel promotion or alternative policies. The analysis evaluates the relative costs of these alternatives in relation to the policies' multiple ends or goals – and this approach distinguishes our analysis from prior assessments. And finally our study examines the potential scope of the contribution of biofuels toward those ends.

The relationships between ends and means are easily overlooked if they are not clearly established. The choice of policy instrument is particularly important because of the way it will often frame the discussion of the policy's objectives. This point has been emphasized by Keohane [24] in the context of discussing the merits of cap-and-trade versus a carbon tax to address climate change. Keohane argues that cap-and-trade will draw attention to the actual level of emissions whereas a carbon tax will draw attention to the level of the tax. In the case of biofuels, by setting policy goals in terms of gallons of ethanol or biodiesel, the debate has focused in many settings primarily on progress toward meeting those goals, and to a much lesser extent on the actual reductions in fossil fuel inputs used, the GHG emission reductions, or the cost of achieving either of these goals. A case in point is the U.S., where a debate has been underway for several years but, until recently, with little attention to the (biofuel) policies' actual effectiveness toward reduced fossil fuel use or lowering GHG emissions, and with no quantitative appraisal of its cost-effectiveness in achieving either of those two underlying goals. By focusing directly on these underlying goals and by developing and applying measures of cost-effectiveness and scope, the analysis presented here evaluates the promotion of biofuels using metrics that connect ends and means.

Here, each alternative biofuel is considered in terms of its costs, fossil fuel inputs, and GHG implications relative to the petroleum-based fuel (gasoline or diesel) it is assumed to be replacing. Biofuels also require land for feedstock production which either directly or indirectly affects carbon emissions. Moreover, government may implement carbon sequestration actions such as forest management and afforestation, although below only sequestration via changes in forest management is considered because it does not require additional lands to be taken out of alternative uses (such as agriculture). Where biofuels are more costly to produce than petroleum-based fuels per unit of energy content, the comparisons here will assume that government policy involves incentives in the form of producer or consumer subsidies at levels necessary to achieve a desired level of biofuel use. This is a conservative approach that will simplify comparisons among policy options and at the same time avoid estimating the magnitude of inefficiencies one can expect with regulatory approaches. The only additional cost in this case will be the cost of public funds required to subsidize biofuels at a level that makes them competitive with conventional fuels. We further assume that consumers' utility is unaffected when biofuels are substituted for fossil fuels; replacing a BTU of fossil fuel energy with a BTU from biofuels involves no direct welfare change at the consumer level.

The substitution of biofuel for fossil fuel has implications in terms of costs as well as the social goals on which biofuel programs have been justified. We assume that when consumers switch from petroleum fuel to biofuel, there is an equal reduction in demand for petroleum fuel which, via market signals, leads to a reduction in production of petroleum fuels. The net effect of the substitution comes from an increase in life-cycle energy and GHG implications for the biofuel and a decrease in the life-cycle energy and GHG implications for the petroleum fuel. The cost-effectiveness of biofuels in achieving each of these goals is defined as the change in cost divided by the change in GHG emissions, or as the change in cost divided by the change in fossil fuel use. These relations are presented explicitly in Appendix A.

The objective is to compare the cost-effectiveness of these alternatives to other interventions that may be lower cost, such as a gas tax or carbon tax, or with energy efficiency improvements, or forest carbon sequestration. A gas tax or energy efficiency improvement that reduces GHG emissions by one metric ton (tons) will at the same time reduce fossil fuel input use. Some biofuels may further one objective (reduced fossil fuel use) but may have an adverse effect in terms of GHG emissions due to their land requirements and indirect effects on terrestrial carbon stores. By contrast, carbon capture and sequestration resulting from changes in forest management will reduce net carbon emissions but may have no significant effect on fossil fuel use. Programs that invest in increased energy efficiency or that promote energy conservation are likely to reduce fossil fuel use and

greenhouse gas emissions, but in different proportions than with a gas tax (i.e., since many energy conservation measures will reduce natural gas consumption and use of electricity, they will have different GHG implications than with gasoline or diesel fuel). These differences in outcomes related to their different objectives make comparing cost effectiveness ratios problematic, because the denominators, or measures of effectiveness, are not equivalent.

This problem has been met in the scientific literature with a number of suggested approaches for multiple-objective or multi-criteria decision analysis (see, for example, [25]). One approach that allows evaluation of cost-effectiveness without assigning weights to different objectives involves comparing interventions, either individually or as combinations, that achieve identical outcomes for all objectives. Depending on the composition of the various alternatives (sets), this approach may offer similar insights about relative costs as in the case of individual actions addressing individual objectives. For any given action such as raising the gas tax, it will generally be possible to find a combination of other actions (e.g., biofuel production plus forest carbon sequestration), that attains the same outcomes (in terms of reduced GHG emissions and reduced fossil fuel use) as the gas tax. For each such action or combination of actions, we can thus compare their cost-effectiveness measures directly. See Appendix A for additional details.

To illustrate this approach, consider a gas tax increase that reduces gas consumption by 100 gallons of gasoline (Fig. 1). This reduction translates into a decrease in fossil fuel inputs of 14.8 MBTU, but also a decrease in GHG emissions of 1.17 ton CO_2-e (CO_2-equivalent).[3] How can these same results be achieved by producing biofuels rather than by raising the gas tax? This same change in fossil fuel input use (−14.8 MBTU) could be attained by producing 157 gallons of corn ethanol. However, producing this amount of corn ethanol is estimated to reduce net GHG emissions only negligibly by 0.10 ton CO_2-e when ILUC effects are included (discussed below). Although the outcomes for a gas tax increase and for production of 157 gallons of corn ethanol are identical in terms of their effects on fossil fuel input use, their effects on GHG emissions are quite different. However, a third intervention, carbon sequestration based on changes in forest management, represents an alternative or independent policy action that, if combined in this case with the production of corn ethanol, could give rise to reductions in GHG emissions overall. Specifically, if the production of 157 gallons of corn ethanol is complemented by a particular amount of forest carbon sequestration, the combination of these two actions could achieve exactly the same outcomes as the gas tax.[4] To summarize, if the production of 157 gallons of corn ethanol is combined with 1.07 tons (CO_2-e) of forest carbon sequestration, the combined effect would be reductions in both fossil fuel input use (14.8 MBTU) and carbon emissions (−1.17 tons), and be exactly identical to the those due to the 100 gallons reduction in gasoline use achieved with the gas tax increase. Thus, with identical outcomes (as summarized in below), and with costs computed in comparable ways, these two different options (a gas tax on the one hand, versus a combination of corn ethanol production and forest carbon sequestration on the other hand) can be compared in a cost-effectiveness framework.

[3] A gallon of gasoline is assumed to contain 0.120 MBTU of energy, require 0.148 MBTU of fossil fuel energy to produce, and generate 97,000 g of CO_2-e per MBTU of energy in fuel.

[4] Forest sequestration can involve an increase the density of biomass in forests (forest management) or it can involve expansion of forest area (afforestation) [46]. We assume here that forest carbon sequestration is achieved via changes in forest management and does not displace agriculture.

5. Data and estimation

The above approach is applied to each of the main biofuels produced or mandated (corn ethanol, soybean biodiesel, and cellulosic ethanol from switchgrass in the U.S., and rapeseed/canola biodiesel in the EU). Sugarcane ethanol produced in Brazil and exported to the U.S. or EU is also evaluated as an alternative to domestically produced biofuels. These biofuels represent the vast majority of current biofuel production and production mandates worldwide.

Estimates of the energy implications of a biofuel policy are based on LCA for the energy inputs utilized to produce, process, and transport biofuels and conventional fuels and the energy contained in the fuel. A similar life-cycle framework is used to estimate the GHG effects. Certain market effects are represented at least implicitly (e.g., [26]) in these LCAs. For example, biofuel energy accounting typically includes assigning an energy credit for the co-products generated during feedstock processing (e.g., distiller dry grains, oilseed meal), as these are generally sold as livestock feed rations. The implicit assumption justifying this energy credit is that market adjustments, or indirect effects in the animal feed market due to the addition of biofuel co-products, will lower the production of animal feed from other sources which in turn will reduce the energy used in traditional animal feed production. Indeed, the market-induced effect underlying the rationale for a co-product energy credit is similar to the indirect land use effect for GHG emissions: production of biofuels has effects in other markets and those market implications for energy and GHGs should be taken into account when evaluating the general-equilibrium effects of biofuel policies.

Central estimates for the key technical and economic parameters including production and processing costs, life-cycle fossil fuel energy, and life-cycle GHG effects are summarized in Table 1 (see Appendix B for additional details). In general, biofuel cost estimates are based on market prices and for those alternatives not yet commercially available (e.g., cellulosic ethanol) on peer-reviewed studies. Assumptions regarding technical parameters for energy and GHG accounting as well as ILUC effects are drawn from the growing scientific literature and from government studies (see Appendix B for details).

In addition to the biofuels being evaluated, three alternative interventions are assessed for comparison purposes: gas tax increases, forest carbon sequestration, and energy efficiency improvements. Each is discussed below.

5.1. Gas tax

The cost of using a tax to reduce gasoline consumption and its associated GHG emissions is analyzed in the literature. A range of studies have estimated the long-run own-price elasticities of gasoline demand in the U.S. West and Williams' [27] estimates center around −0.51; Parry and Small [28] conclude that the best consensus long-run elasticity is −0.55. An earlier meta-analysis found a median value of −0.43 [29]. Similar elasticities lead West and Williams [30] to conclude that the initial marginal cost of a gas tax increase that results in one less gallon of gasoline consumed is \$0.26/gallon (based on prices and U.S. gas taxes in 1997). Their estimate takes account of the long-run responsiveness in miles-per-gallon to gas price, and also the complementarity between gasoline consumption and leisure and hence the effects on the costs of public funds. When applied to current taxes and prices, and using the Parry and Small "consensus" elasticity estimate of −0.55, these values produce cost estimates of \$1.46/MBTU for reducing fossil fuel use and of \$18.60/ton for GHG reductions.[5]

[5] The marginal cost relation in West and Williams [30] is based on a gas price of \$1.19, gas tax of 0.367, a marginal cost of funds of 1.02, and own-price elasticity of

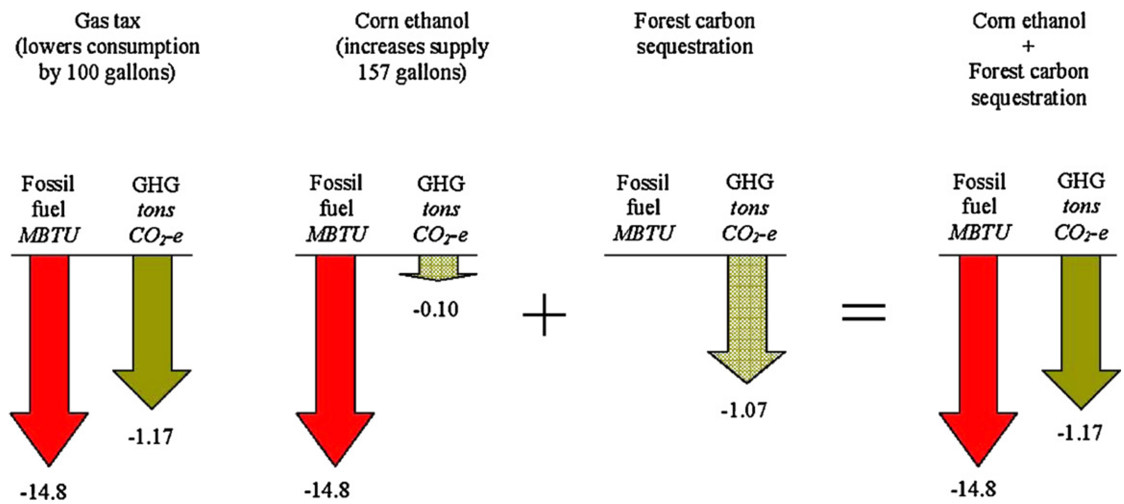


Fig. 1. Hypothetical effects of specific increases in the gas tax, corn ethanol production, and forest carbon sequestration on fossil fuel use and greenhouse gas (GHG) emissions.

For the EU, the estimated responsiveness of gasoline consumption to the gas tax is based on a central demand elasticity estimate of −0.75 [31]. This differential between the U.S. and European own-price gasoline demand elasticities is consistent with Espey's [29] meta-analysis. When the West and Williams marginal cost relationship is adjusted to reflect EU gasoline prices, taxes, and the own-price gasoline demand elasticity, the results indicate that an additional 1% reduction in EU gasoline consumption requires an increase in the gas tax of $0.065/gallon, the marginal cost of which is $2.76/gallon. The EU costs to reduce fossil fuel use and GHG emissions with a gas tax are then $18.60/MBTU and $237/ton of GHGs, which in both cases is more than 12 times as costly as in the U.S. The marginal costs associated with increasing the gas tax are greater in the EU primarily because gasoline taxes are already considerably higher there than in the U.S., increasing the distortionary costs to a larger extent.

5.2. Forest carbon sequestration

Carbon sinks are often viewed as a potentially low-cost offsets to GHG emissions and an alternative to reduced fossil fuel use or fuel switching. Carbon sequestration alternatives include increasing soil carbon in agricultural lands, and also carbon capture and storage for which carbon would be sealed in abandoned oil and gas wells or injected into other geologic features. Current evidence suggests, however, that forest sequestration may be lower cost than other alternatives. Forest carbon sequestration options are recognized under the Kyoto protocol, although issues of monitoring and leakage have given rise to uncertainty and confusion about implementation. Nevertheless, there are now many studies that have evaluated the potential as well as the costs of forest carbon sequestration either by afforestation (increasing forested areas) or by forest management (managing existing forests in ways that will increase the amount of sequestered carbon with, for example, lengthened rotations; for more detail see van Kooten and Sohngen [32] as well as [33]).

The current analysis focuses on employing carbon sequestration options that, unlike biofuels, do not displace food production and so are unlikely to involve significant adverse ILUC effects. These non-food-displacing options may however not always be the lowest cost alternatives. Richards and Stokes [43] point to "conservative estimates" by Stavins [34] of costs around $33/ton CO_2-e for these options. Moreover, there are also questions about implementation, leakage and additionality that argue for erring on the conservative side. Therefore, this study adopts Stavins's [34] $33/ton CO_2-e as the baseline cost estimate for the U.S. For the EU, a cost of $118/ton CO_2-e, is assumed based on estimates that carbon sequestering forest management approaches are 3.6 times as costly in Europe [32]. Importantly, these costs do not assume that changes are achieved via subsidies, and hence the costs of public funds are not included. A regulatory approach or combination of taxes and subsidies could presumably achieve increased carbon sequestration with no net fiscal cost.

5.3. Energy efficiency improvements

Numerous studies address the potential, obstacles, and cost of improved energy efficiency in industry, buildings, and residential uses (e.g., [35]). Recent analyses of mitigation options for GHG include energy savings investments in transportation sectors, but also in energy supply, buildings and industry ([36], chapter 11, Table 11.3). A recent study of the potential for low-cost energy efficiency improvements in the U.S. by the McKinsey Company [37] finds that energy efficiency offers a large, low-cost energy resource, but that significant hurdles need to be overcome, primarily at the policy level. The McKinsey study concludes that interventions to encourage energy efficiency gains could yield a recurring contribution equivalent to more than 9 quadrillion BTUs (9×10^{15}) per year, or roughly 23% of projected total annual U.S. energy demand, which at the same time would lower annual GHG emissions by more than 1 Gt (gigaton). The IPCC [36] analysis projects more than 10 Gt potential annually for GHG mitigation globally through energy savings from energy supply, buildings and industry ([36], Table 11.3), a value that is broadly consistent with the McKinsey and other studies. The estimates from Granade et al. [37] are used here to characterize a non-transport alternative energy policy to reduce fossil fuel energy use and GHG emissions for the U.S. All potential positive net present value energy efficiency improvements represent a total level of annual energy use reductions that is equivalent to a 40% reduction in gasoline consumption. These energy efficiency improvements are estimated be possible from a wide range of actions including information and education, incentives and financing, changes in codes and standards that could eliminate significant barriers to energy efficient practices and technologies.

demand for gasoline of 0.46. The reduction in fossil fuel input energy per gallon of gasoline avoided is 0.148 MBTU, and the reductions in GHG emissions amount to 0.097 tons per MBTU of gasoline.

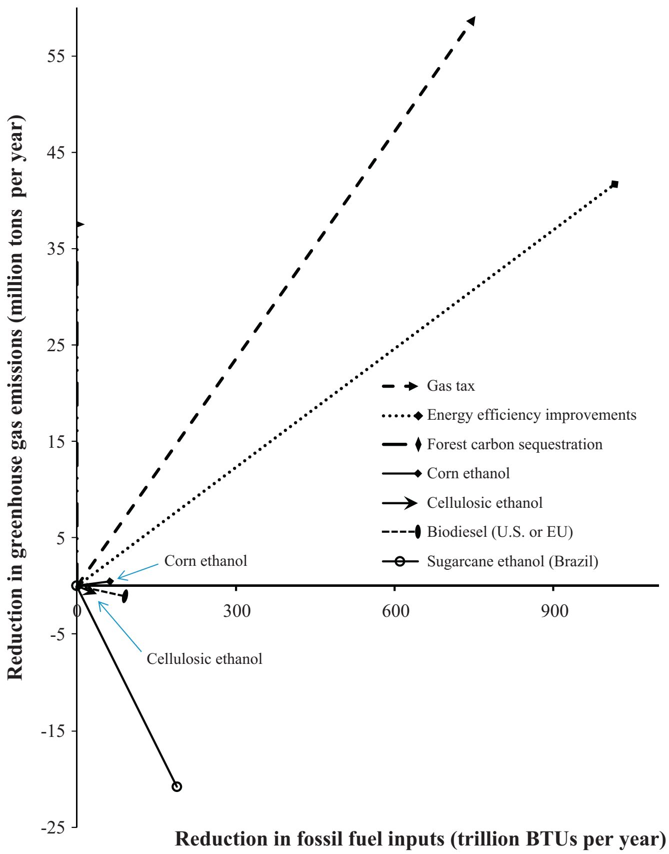


Fig. 2. Reductions in fossil fuel input use and greenhouse gas emissions achievable for $1 billion under alternative policies.

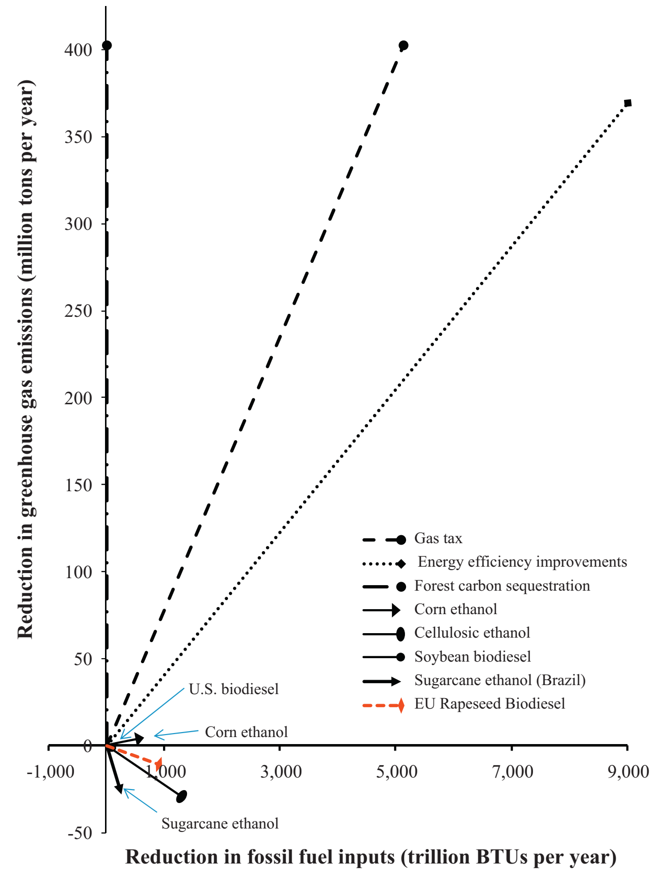


Fig. 3. Potential scale of reduced fossil fuel input use and greenhouse gas emissions with alternative policies.

6. Results

A useful starting point is to make some straightforward observations. There are significant differences in the cost of production among biofuels and also in the energy content per gallon of fuel (Table 1). The amounts of fossil fuel energy inputs required per MBTU of energy-in-fuel, however, vary even more (from 0.04 to 0.66 per MBTU) due to the large differences in input energy required to produce some biofuels. When biofuel costs are measured per unit of reduction in the use of fossil fuel inputs, these cost relationships also vary widely among biofuels and between biofuels and options such as a gas tax or energy efficiency improvements. Similarly, large differences emerge when costs are represented for reducing GHG emissions, including "infinite costs" for those cases where GHG emissions are estimated to increase. These simple cost measures, however, relate the costs of each option to incremental changes for only one policy objective at a time, and therefore may provide a misleading basis for comparison when multiple objectives are at issue.

6.1. Costs and scale of individual alternatives

To visualize the underlying differences among biofuels and other possible policy alternatives, our results are first presented as simple two-dimensional vectors (Fig. 2). Each dimension represents one of the two policy objectives – reduction in fossil fuel use and reduction in GHG emissions. For purposes of comparison, each vector is chosen to reflect the reductions achievable at a cost of $1 billion. The results show that all of the biofuel options considered have an implicitly higher cost relative to non-biofuel options.

A similar vector representation illustrates the scope or potential scale of production of the examined alternatives. For biofuels, these are based on the feasibility of producing sufficient feed stocks (Fig. 3). The graph shows the limitations on biofuels for achieving significant reductions in fossil fuel input use and GHG emissions as compared to the alternatives. The reductions possible when relying on first-generation biofuels (corn and oilseed-based) are estimated to be less than 1% of fossil fuel use (or about 2% of U.S. petroleum consumption). The exception is cellulosic ethanol where a 1.5% reduction of fossil fuel use (equivalent to 2.5% of petroleum consumption) may be possible. This estimate however is uncertain given cellulosic ethanol's high estimated cost per gallon and the current lack of any commercial production in the U.S. under existing subsidies. By contrast, a gas tax, energy efficiency improvements, and forest carbon sequestration all have the potential to achieve 5% to 10% reductions in GHG emissions. Combining gas tax increases and energy efficiency improvements has the potential to reduce fossil fuel use by more than 15%, or to reduce petroleum fuel use by more than 35%.

6.2. Equivalent outcomes compared for combined policy alternatives

6.2.1. Incremental cost-effectiveness ratios

Here one or more policy interventions are combined such that they attain identical sets of outcomes which then allows for comparison of the interventions' costs for equivalent results. Using a gas tax increase as the base for these comparisons, we combine biofuel production with forest carbon sequestration in proportions that produce the same reductions in fossil fuel input use and GHG emissions as a gas tax.

Table 1
Biofuel marginal cost, energy and greenhouse gas accounting – and alternatives.

	U.S. biofuel alternatives				EU biofuel alternatives	
	Corn ethanol	Biodiesel (soybean)	Cellulosic ethanol (switchgrass)	Sugarcane ethanol (Brazil)	Biodiesel (rapeseed)	Sugarcane ethanol (Brazil)
Costs and energy:						
Cost of production ($/gallon)	1.80	3.20	3.00	1.30	3.22	1.30
Energy per gallon (BTU/gallon)	76,300	118,000	76,300	76,300	118,000	76,300
Cost of production ($/M BTU)[a]	23.6	27.1	39.7	17.0	27.3	17.0
Fossil fuel input use (BTU/gallon)	50,500	44,890	5800	3000	42,000	3000
Fossil fuel inputs per unit of energy in fuel (BTU/BTU)	0.66	0.38	0.08	0.04	0.36	0.04
Fossil fuel use:						
Cost per reduction in fossil fuel use when substituted for conventional fuel ($/M BTU)	15.70	16.30	24.90	5.00	19.50	7.30
Cost to reduce fossil fuel use with gas tax ($/M BTU)	1.48	1.48	1.48	1.48	18.66	18.66
Cost to reduce fossil fuel use with energy efficiency improvements ($/M BTU)	0.98	0.98	0.98	0.98		
Greenhouse gases:						
Change in GHG emissions when substituted for conventional fuel (g/M BTU)	−4100	9180	26,400	48,140	4300	48,140
Cost per reduction in GHG emissions when substituted for conventional fuel ($/M BTU)	2417	∞	∞	∞	∞	∞
Cost per reduction in GHG emissions with a gas tax ($/ton CO_2-e)	19	19	19	19	237	237
Cost per reduction in GHG emission with carbon sequestration (afforestation) ($/ton CO_2-e)	26	26	26	26	93	93

[a] Conventional fuel costs are $16.67 per million BTU for gasoline and $17 per million BTU for petroleum diesel.

The ratios of these cost-effectiveness measures are summarized in Table 2 and estimated at the incremental level equivalent to a 1% reduction in gasoline consumption. For the U.S., costs for each biofuel option are added to the costs for an amount of forest carbon sequestration sufficient to achieve the same combined reductions in fossil fuel use and GHG emissions as a U.S. gas tax increase. Under this scenario, corn ethanol is found to be 13.6 times as costly as raising the gas tax; and both soybean biodiesel and switchgrass-based cellulosic ethanol are about 19.3 and 20.6 times as costly. The option of importing sugarcane-derived ethanol from Brazil is 7.7 times as costly as a gas tax increase. When compared to the costs for non-transportation energy efficiency improvements estimated by Granade et al. [37], U.S.-produced biofuels are at least 20 times more costly.

Results for the EU differ considerably from those for the U.S. First, domestic European biodiesel production is found to be as costly as in the U.S. ($27.3 versus $27.1/MBTU, Table 1). However, when compared to a gas tax increase, the relative differences in cost are much smaller. For example, production of biodiesel from rapeseed and combined with forest carbon sequestration is estimated to be only about 1.9 times as costly in the EU as a EU gas tax increase (compared to 19.3 for U.S., Table 2). This finding is due to the 11 times greater cost of reducing gas consumption with a gas tax in the EU than in the U.S., due to the already high gas taxes in Europe. EU gas taxes average $2.87/gallon [38] compared to $0.40/gallon in the U.S. (U.S. Energy Information Agency 2009). Despite the higher EU taxes, imported Brazilian ethanol is still 40% less cost-effective for the EU than a gas tax increase. Costs for forest carbon sequestration in the EU are also higher than in the U.S. ($26 versus $93/ton CO_2-e, Table 1) because Europe features more limited forested areas and higher population densities.

The incremental cost-effectiveness ratios reported in Table 2 provide a simple metric that captures the large differences in costs among alternative means to achieve the ends of reduced fossil fuel use and GHG emissions. The results underscore how deceptive a superficial accounting of cost can be: biofuel costs per gallon differ by relatively small amounts, in a range between 70% and 170% of the cost of petroleum fuels (Table 1). Thus, when considering only the cost per gallon of biofuel, and comparing it to the cost of a gallon of gasoline, it is easy to overlook the fact that the connection between using a gallon of biofuel and the resulting reductions in either fossil fuel use or GHG emissions is extremely weak.

6.2.2. *Non-incremental changes*

Next, the non-incremental changes in biofuel production as proposed by the various national programs are evaluated by comparing their cost-effectiveness over a range of larger scale interventions. The maximum potential for each alternative is assessed in comparison to the scale of the desired reduction in fossil fuel use and GHG emissions. Levels of potential production are based largely on governments' future targets. For example, the revised U.S. renewable fuels standard targets (as of 2010) for the year 2022 calls for 15 billion gallons of corn ethanol, 1 billion gallons of soybean biodiesel, 16 billion gallons of cellulosic ethanol, and 4 billion gallons of "other advanced biofuels." In the EU, the overall renewable fuels target is to provide 10% of transportation fuels, but the European Parliament has endorsed having 40% of that target come from "second-generation" renewable that, unlike oilseed-based biodiesel, do not compete in food and farmland markets [39]. Therefore, the resulting 'net' target of 6% of EU transportation fuel is assumed as the upper bound on biodiesel production. Imports of Brazilian sugarcane-based ethanol are limited to predicted growth

Table 2
Incremental cost-effectiveness comparisons.

Ratio of incremental cost-effectiveness of each option compared to:		
	Gas tax increase	Energy efficiency improvements[a]
U.S. policy options		
Gas tax	1.0	1.5
Corn ethanol	13.6	20
Biodiesel (soybean)	19.3	29
Cellulosic ethanol (switchgrass)	20.6	31
Sugarcane ethanol (Brazil)	7.7	12
EU policy options		
Gas tax	1.0	na
Biodiesel (rapeseed)	1.9	na
Sugarcane ethanol (Brazil)	1.4	na

[a] Evaluated at the level of a 1% reduction in gasoline consumption.

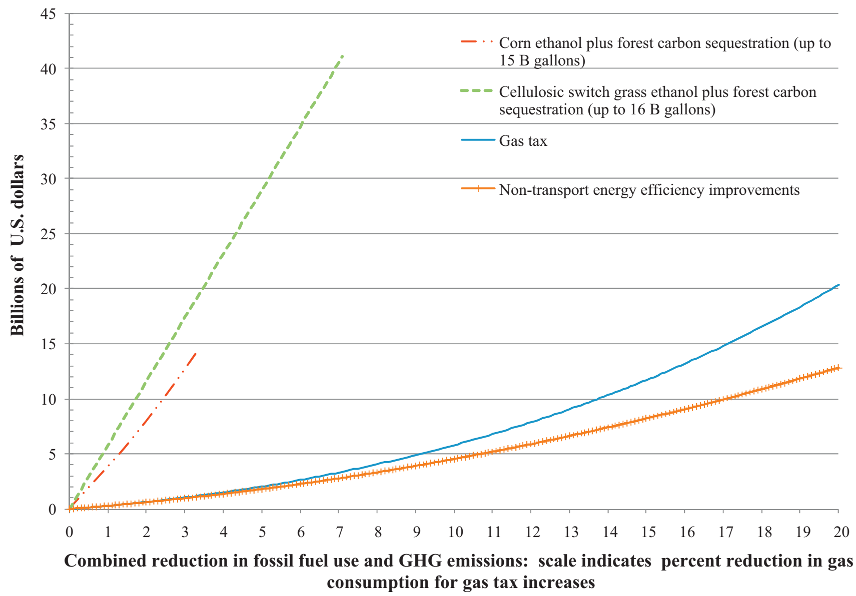


Fig. 4. U.S. costs and scope for reducing fossil fuel use and GHG emissions with alternative interventions.

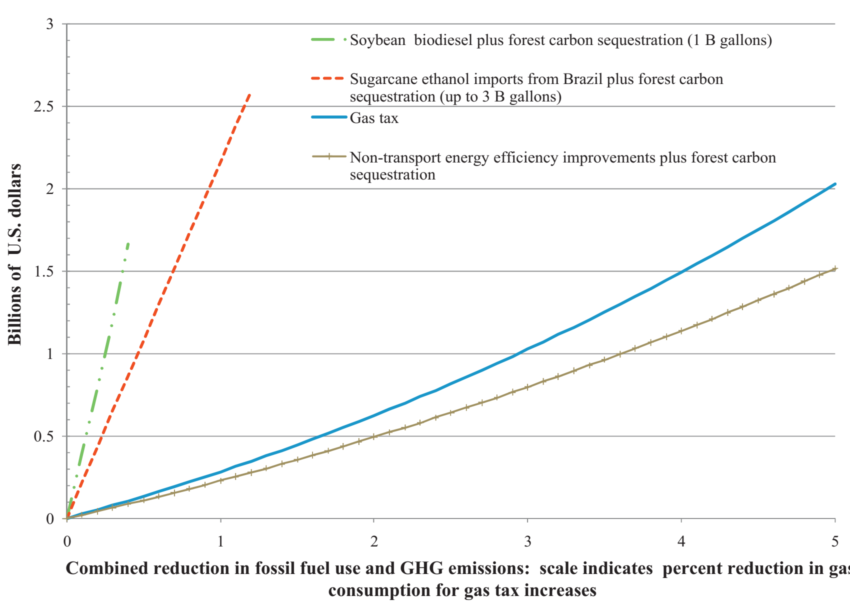


Fig. 5. U.S. costs and scope for reducing fossil fuel use and GHG emissions with alternative interventions.

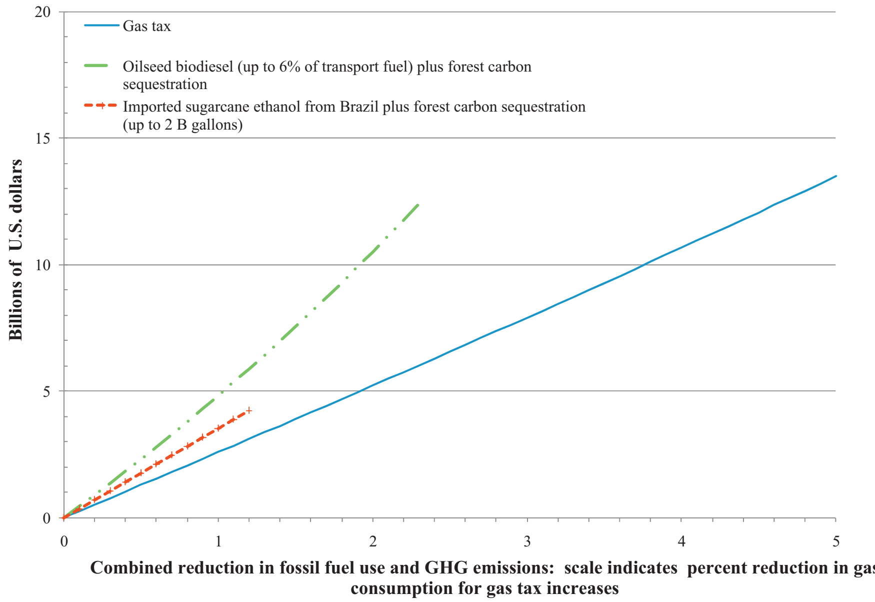


Fig. 6. EU costs and scope for reducing fossil fuel use and GHG emissions with alternative interventions.

in production and export capacity. Brazilian total exports are forecasted to rise to 6.6 billion gallons by 2025 [40], from which we assume a limit of 3 billion gallons available for U.S. imports and 2 billion gallons available for EU imports (other importers of Brazilian ethanol include, for example, Japan).

When biofuel production increases by substantial amounts such as those prescribed in the above policy targets, the marginal costs of biofuel production change. Details for the estimation of the marginal cost relations for biofuel production are provided in Appendix B. In the case of forest carbon sequestration, constant marginal costs are assumed due to the uncertainty surrounding the estimates themselves and their likely trajectory across levels. A constant marginal cost is also assumed for Brazilian ethanol given the lack of supply function estimates.

Both the costs and scope of outcomes for each policy under investigation are illustrated in Figs. 4 and 5 for the U.S. and Fig. 6 for the EU. In Fig. 4, the cost and scope for a gas tax increase are shown for a range of reductions equivalent to a 20% reduction in U.S. gasoline consumption, or about 5% of total U.S. fossil fuel use and 4.5% of U.S. GHG emissions. These costs and outcomes are compared to those for the U.S. 15 billion gallon corn ethanol target, which achieves substantially less than a gas tax – only one-seventh as much (equivalent to a 3.1% reduction in U.S. gasoline consumption, which reduces total US fossil fuel use by only about 0.75%). Indeed, implementation of energy efficiency improvements as estimated in Granade et al. [37] have the potential of achieving the same reductions as with a gas tax, but at a lower cost.

Costs and scale for cellulosic ethanol are also depicted in Fig. 4, indicating much greater costs and somewhat larger potential scope than with corn ethanol. At a cost of $41 billion, cellulosic ethanol (and complementary forestry actions) is estimated to reduce fossil fuel use by an amount equivalent to a 7% reduction in gas consumption.

Fig. 5 is scaled differently than Fig. 4 given the much lower potential reductions from biodiesel and imported Brazilian ethanol (biofuels were grouped in Figs. 4 and 5 to allow appropriate scaling). The very limited contribution and high cost of biodiesel in the U.S. is evident in Fig. 5, where the gain attainable with 1 billion gallons is estimated to be equivalent to a reduction in gasoline consumption of less than 0.7% – a result that could be achieved with a gas tax increase of about $0.03/gallon.

Imports of sugarcane-based ethanol from Brazil are also found to be less cost-effective than either a gas tax increase energy efficiency improvements, but the differences are significantly smaller than for the other biofuels (Table 2). The scope, however, is limited by the growth in Brazilian production, so that for the U.S. energy and GHG objectives, future imports from Brazil are estimated to have a potential gain equivalent to a reduction in gasoline consumption of 1.2%, an amount that could be achieved by a gas tax increase of $0.053/gallon.

Fig. 6 depicts the corresponding results for the EU. The horizontal scale is the same as in Fig. 5, indicating that the scope for reductions from biodiesel and imported Brazilian ethanol are limited to reductions comparable to 2.3% and 1.2% of gasoline consumption, respectively. At those maximum levels the reductions in fossil fuel inputs correspond to 0.5% of fossil fuel consumption for biodiesel and 0.25% for imported ethanol. No estimates of the cost for non-transportation energy efficiency improvements were available for the EU. However, another McKinsey report for Belgium (McKinsey [42]) suggests potential gains similar to those for the U.S.

The cost-effectiveness measures presented focus on the two main goals of biofuel policies, reductions in fossil fuel use and reductions in GHGs. Other potential beneficial effects such as increased rural jobs do not appear to be large enough to substantially alter these results. Other potential negative effects include the effects of feedstock production on water use and local pollution, as well as distributional effects related to food prices and the poor. On balance the existing evidence on these other aspects of biofuel policy do not suggest that a comprehensive analysis would be significantly more favorable toward biofuels. Some indirect effects related to alternatives such as gas taxes, energy efficiency improvements and forest carbon sequestration are also omitted from this analysis.

7. Concluding comments

All government actions should have clearly defined objectives and alternative approaches should be judged in relation to those objectives: Will they achieve the stated goals? At what cost? Frequently the focus of attention becomes misdirected toward surrogate agendas or metrics that do not measure progress toward the

intended goal, resulting in well-intentioned but errant activities that are ineffective, wasteful or even counterproductive.

The present analysis raises doubts about biofuels in relation to the specific objectives for which they have been promoted. As a means of reducing fossil fuel use and GHG emissions, domestic production of biofuels in the U.S. is found to be 14–31 times as costly as alternatives like a gas tax increase or promoting energy efficiency improvements (based on comparable reductions in both fossil fuel use and GHG emissions).

In addition, the scale of biofuels' potential contribution toward U.S. energy and climate policy goals is extremely small. Although the Energy Independence and Security Act of 2007 stipulates ambitious targets of expanding biofuels in the U.S., those mandates' contribution to the underlying goals of reduced fossil fuel use and reduced GHG emissions are negligible. The U.S. mandate of 15 billion gallons of corn ethanol may represent 10% of current gasoline consumption on a gallon-for-gallon basis, but the effect of this production level is equivalent to only a 3.1% reduction in gasoline consumption, or less than 0.75% of total U.S. fossil fuel use (including coal, natural gas, heating oil, etc.). The annual target of 1 billion gallons of soybean biodiesel represents a net reduction equivalent to only 0.1% of U.S. fossil fuel consumption. And the ambitious 16 billion gallon target for cellulosic ethanol in 12 years (of which none is currently commercially produced), represents a net fossil fuel contribution equal to about 1.7% of current U.S. total fossil fuel use if based on switchgrass. In fact, all of these biofuel mandates combined, if achieved, would have the same effect on total U.S. fossil fuel use as a $0.25/gallon gas tax increase, but at an estimated total social cost of $67 billion versus $6 billion with a gas tax.

The most striking result, however, may be the lack of evidence that biofuel policies can be expected to achieve significant reductions in GHG emissions, and that they may actually increase emissions.[6] The cost-effectiveness comparisons presented here assume that biofuel production activities (all of which either increase GHG emissions or reduce them negligibly) would be combined with forest carbon sequestration so that, in combination, they could match the reductions in both fossil fuel use and GHG emissions achievable by a higher gas tax. Although this pairing of biofuels with forest management has made it possible to compare the costs of alternative policies for identical changes in multiple objectives, the combination is an artificial one. Each intervention can also be considered independently, while recognizing the differences in their contribution to different ends. Given biofuels' high cost and small gains in fossil fuel reductions, promoting forest carbon sequestration on its own merits to reduce GHG emissions may be justifiable independently.

By contrast, the import of sugarcane ethanol from Brazil comes closer to being cost-effective (relative to a gas tax increase) than do domestically produced biofuels. The cost per BTU is lower than the cost of gasoline. However, the cost-effectiveness of Brazilian sugarcane ethanol is still 7.7 times that of an increased gas tax in the U.S. when sugarcane ethanol is combined with forest carbon sequestration to compensate for the significant ILUC effects in Brazil. Furthermore the scope of this alternative is quite limited. An optimistic level of 3 billion gallons of imported Brazilian ethanol by 2025 would be equivalent to only a 1.3% reduction in U.S. gasoline consumption or just 0.3% of total U.S. fossil fuel use.

For the EU these comparisons appear somewhat different. Because of Europe's already high gas tax, the cost-effectiveness ratio for domestic biofuel production in the EU is more favorable than in the U.S., but not positive. Here too imports of Brazilian ethanol come closer to being cost-effective relative to gas tax increases (about 40% more expensive than further gas tax increases). Yet, like in the U.S., the scope would remain quite small due to sugarcane ethanol's limited global production potential.

The framing of a policy objective can implicitly suggest very different measures of success, and hence can give rise to very different perceptions about a policy's potential or realized successes. By emphasizing the capacity to produce and sell biofuels at prices that are not too different per gallon than gasoline, attention has been focused on how many gallons can be produced. But this attention to gallon-for-gallon substitution has distracted policy-makers from acknowledging that biofuel production may occur without actually generating the desired reductions in fossil fuel use or GHG emissions. When framing the analysis directly in terms of the key objectives, however, a different picture emerges. Judged on the basis of reducing fossil fuel use and GHG emissions, the results presented here suggest that these policies have been ineffective and highly costly, producing negligible reductions in fossil fuel use and significant increases, rather than decreases, in GHG emissions.

Advocacy of biofuels by some observers stems, in part, from concern that conserving energy via gas tax incentives or promoting energy efficiency improvements will not adequately substitute for liquid fuels that dominate the transportation sector. The convenience of liquid fuels for transportation is an important consideration. However, given the small fraction of current energy use that could be satisfied with biofuels, as well as the recent introduction of commercial electric cars, substitutions among types of energy and between sectors could easily achieve similar or larger shifts away from gasoline and diesel. For example, with electric cars coming to market in growing numbers the potential for substituting electricity for liquid fuels will increase. At the same time the production capacity for renewable sources of electricity such as wind has been expanding rapidly in recent years; and the Energy Information Administration estimates that levelized electricity costs for new wind power plants by 2020 are $0.095/kW h compared to $0.105/kW h for coal and $0.08/kW h for natural gas [41]. Nevertheless, in a context with unintended consequences and policies aimed at multiple objectives, policy-makers should carefully evaluate the connection between means and ends to ensure that any alternative energy option being considered will achieve the stated objectives at an acceptable cost.

Appendix A. Derivation of multiple-objective cost-effectiveness measure

Our evaluation of biofuels and other interventions is framed as follows. We characterize a model that includes two liquid fuels, a conventional petroleum-based fuel and a biofuel, with associated costs, carbon emissions and land use implications. The conventional petroleum-based fuel (e.g., gasoline or petroleum diesel) has a cost $C_p(q_p)$, a constant rate δ_p of fossil fuel input requirements, and an associated carbon emissions rate β_p. An alternative biofuel has a production cost $C_b(q_b)$, fossil fuel inputs required at a rate δ_b, and carbon emissions rate β_b. We assume $C_i' > 0$, $C_i'' > 0$, $\beta_p > \beta_b$ and $C_p(q_p) < C_b(q_b)$. Units of fuel are normalized in equivalent British thermal energy units (BTUs). We further assume that biofuel

[6] The U.S. Renewable Fuels Standards were modified by the Environmental Protection Agency in February 2010. The changes included requiring all biofuels to achieve specified reductions in GHG emissions when ILUC effects are included. All existing facilities producing corn ethanol, however, are exempted from the requirement of a 20% GHG reduction. For advanced biofuel plants and for future ethanol plants, the new EPA rules made a "determination" that these biofuels will be able to meet or exceed these new thresholds (including 50% GHG reductions for advanced biofuels and 60% for cellulosic). These determinations, however, are not based on what any existing facilities have currently achieved. The ruling allows the EPA to relax these requirements by 10% GHG reductions based on future assessments. Overall these rule changes offer little evidence that U.S. biofuels will generate GHG reductions in the foreseeable future.

production requires land, $L_b(q_b)$ for feedstock production, and that either directly or indirectly this land input gives rise to carbon emissions, τ_b. We assume that although fossil fuel production requires land at some level, no change in land use is likely to be involved when changing conventional fuel production levels over the relevant range. Government may also engage in carbon sequestration actions such as forest management and afforestation, s, where the level of these actions, q_s, comes at a cost $C_s(q_s)$, and producing a rate of carbon absorption, ψ_s. Below we will assume that sequestration via changes in forest management does not require additional lands to be taken out of alternative uses such as agriculture. To the extent that biofuels are more costly to produce than petroleum-based fuels, we assume that government policy involves incentives such as producer or consumer subsidies to achieve a desired level of biofuel use. We further assume that consumers' utility is unaffected when biofuels are substituted for fossil fuels; replacing a BTU of fossil fuel energy with a BTU from biofuels involves no direct welfare change at the consumer level.

For each of the two main goals, greenhouse gas emissions reductions (dG) or reduced fossil fuel use (dF), we can express a measure of the incremental cost-effectiveness (CE) as:

$$CE_b^F = \frac{(MC_b - MC_p)}{(\delta_b - \delta_p)} = \frac{(MC_b - MC_p)}{dF_b}, \tag{1}$$

$$CE_b^G = \frac{(MC_b - MC_p)}{(\beta_b + \tau_b L_b - \beta_p)} = \frac{(MC_b - MC_p)}{dG_b}. \tag{2}$$

We want to compare the cost-effectiveness of these alternatives to other interventions that may be lower cost, such as a gas tax or carbon tax, energy efficiency improvements, or forest carbon sequestration. These policy mechanisms are recognized to reduce fossil fuel use, F, and GHG emissions, G, directly. In the case of a gas tax, t, we can intuitively write

$$CE_t^G = \frac{MC_t}{dG_t} \quad \text{and} \quad CE_t^F = \frac{MC_t}{dF_t},$$

where MC_t is the marginal social cost associated with the introduction of a gas tax.

In the case of direct sequestration of carbon in forests, s, we have

$$CE_s^G = \frac{MC_s}{\psi_s}.$$

To create comparable cost-effectiveness measures for actions involving multiple outcomes, multiple actions can be combined and compared. For example, an action x_1 that achieves specific outcomes in two dimensions v_1 and v_2 (e.g., GHG and fossil fuel reduction) can be compared to a combination of alternative actions x_2 and x_3 that achieve the same outcomes v_1 and v_2. We can generalize the multiple-objective problem in terms of an action involving inputs q_i, and a cost $C_i(q_i)$ resulting in a vector of outcomes $v_i = v(v_1, v_2, v_3, \ldots, v_m)$. In a problem involving m objectives, a given vector of outcomes can be produced by a linear combination of $m-1$ vectors of actions $x_1, \ldots, x_m$, where $x_i = x_i(v_1, v_2, v_3, \ldots, v_m)$, provided that the vectors are independent. We simply solve the simultaneous equations for the equivalence between vectors of outcomes among multiple actions. For each action or combination of actions we can then compare their cost-effectiveness,

$$CE_i = \frac{C_i}{x_i}, \tag{3}$$

where each action or combination has been chosen so that the vectors of outcomes, v, are the same.

Appendix B. Supplemental materials

Supplementary materials associated with this article can be found, in the online version, at doi:10.1016/j.rser.2011.07.118.

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